Effect of Working Environment on Stiction Mechanisms in Electrostatic RF-MEMS Switches

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Abstract. In this work, an in depth investigation of the major stiction mechanisms occurring in electrostatic RF-MEMS switches is presented. Stiction is caused by two main mechanisms: dielectric charging and meniscus formation resulting from the adsorbed water film between the switch bridge and the dielectric layer. The effect of each mechanism and their interaction were investigated by measuring the adhesive force under different electrical stress conditions and relative humidity levels. An atomic force microscope (AFM) was used to perform force-distance measurements on the nanoscale. The study provides a comprehensive understanding of the phenomena and highlights the crucial role of the working environment hence of the packaging.

1. Introduction

Among various reported reliability concerns for electrostatic capacitive MEMS switches, the dielectric charging and its resulting stiction is considered the main failure mechanism of these devices [1]. On the other hand, capillary condensation of water vapour results in the formation of meniscus bridges between contacting and near-contacting asperities of two surfaces in close proximity to each other. This leads to an intrinsic attractive force, which may lead to high adhesion and stiction [2]. The meniscus formation is also reported to be highly affected by the electric field [3, 4]. Thus, the applied bias used to actuate MEMS switches and the resulting dielectric charging are expected to affect the meniscus formation at the interface between the switch bridge and the dielectric film. Therefore, the adhesion or stiction between the switch bridge and the dielectric film could be also affected by the meniscus formation. The individual impact of the two different stiction mechanisms (charging induced and meniscus force induced) and their interaction under different electrical stress conditions and relative humidity levels are not understood and have not been studied before. Moreover considering the limitations in the accurate assessment of working environment within packaged RF-MEMS microvolume, (which in worse case scenario may even drift with time), and the impact of environment on the device performances, the relevance of accurate investigation technique is apparent.

In this study a novel characterization technique is presented in order to study different stiction mechanisms which exist in MEMS switches. The proposed methodology makes use of the AFM tip in order to simulate a single asperity contact with the dielectric surface [5, 6]. For the first time the adhesive force measured on the nanoscale under different relative humidity levels and electrical stress conditions is presented. The induced surface potential over the dielectric surface was measured, and used in order to explain the obtained results. Force-distance measurements was performed on the nanoscale and are used to measure the adhesive force. The individual and combined influence of the meniscus force and dielectric charging on adhesive force was studied. This provides an accurate evaluation of the individual effect of each stiction mechanism.

Finally, a correlation between the obtained nanoscale results and the literature reported data from MEMS switches measurements, was performed.

2. Experimental Details

The investigated samples consist of PECVD SiNx films with 300 nm thickness deposited over 500 nm Au layers, which were evaporated over Si substrates (see inset figure in Fig. 1). Since no photolithography steps are required in order to prepare the required samples, the proposed technique provides a low cost and quite fast assessment solution compared to other characterization methods. The adhesion experiments were performed under different relative humidity levels in order to study the effect of meniscus force. For each humidity level, the adhesive force was measured while different bias amplitudes were applied to the Au layer underneath the SiNx film. Due to the dielectric charging, the SiNx film is charged and this results in an induced surface potential over the dielectric film. The applied bias, therefore, corresponds to the voltage used to actuate the MEMS switch and/or the induced surface potential over the dielectric film due to the dielectric charging.

Force-distance measurements were used to measure the adhesive force between the AFM tip and the SiNx film as well as the adsorbed water film thickness over the SiNx surface [2]. An example of the force-distance curve for the investigated samples is presented in Fig. 1.

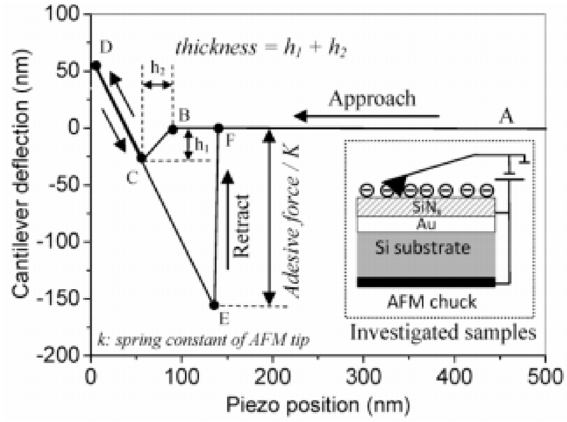


Fig. 1. Force-distance curve for the investigated samples.

The force-distance measurement starts at a large separation (point A) where there is no deflection of the cantilever. As the piezo moves towards the sample, a sudden mechanical instability occurs between point B and point C, and the tip jumps into contact with the adsorbed water film and wicks up around it to form a meniscus. The cantilever bends downwards because of the attractive meniscus force acting on the tip. As the piezo further approaches the SiNx surface, the deflection of the cantilever increases while the tip travels in the water film and eventually contacts the underlying SiNx surface at point C, and then the cantilever starts to bend upwards. Once the piezo reaches the end of its designated ramp size at point D, it is retracted to its starting position. The tip goes beyond zero deflection (point E) and enters the adhesion region. At point E, the elastic force of the cantilever becomes equivalent to the adhesive force, causing the cantilever to snap back to point F. The piezo travel distance used in this study is 500 nm which is comparable to the air gap of MEMS switches.

The adhesive force, which is the force needed to pull the tip away from the sample, can be calculated from the force distance curve by multiplying the vertical distance between E and F with the stiffness of the cantilever as explained in Fig. 1. Also, as the tip travels in the adsorbed water film from point B to C, it is deflected as well. The tip deflection occurs in the same direction as the piezo travels for the AFM used in this study. The water film thickness is therefore the sum of the travel distance of the piezo (h_1), and the deflection of cantilever (h_2) as highlighted in Fig. 1 [2].

3. Results and Discussion

A. Effect of meniscus formation when no-bias is applied

Figure 2 shows that the adhesive force increases considerably when the relative humidity (RH) increases from 1% to only 20%, and the increase tends to saturate at larger RH. The measured thickness of the adsorbed water film over the SiNx surface also increases with humidity as highlighted in the figure. The increase of the water film thickness enhances the meniscus formation, and consequently results in increasing the adhesive force. Though the measured increase in the water film thickness when increasing RH from 1% RH to 80% RH is found to be relatively small, the adhesive force increases considerably. In addition, when the RH increases, the meniscus becomes easier to form and more difficult to rupture [7]. This leads to stronger attractive capillary force between the tip and the sample, and hence larger adhesive force with increasing the RH. The considerable change in the adhesive force when RH increases to only 20% indicates that the SiNx material is very sensitive to any tiny amount of water molecules adsorbed over its surface.

B. Effect of applied bias on adhesive force

The separate and combined effect of the two mentioned stiction mechanisms were studied by using three different groups of samples (A, B, and C). Group A and B were dehydrated just before performing the experiments through two cycles of heating (150 °C) and cooling steps under vacuum.

This removes a considerable amount of the adsorbed water over the dielectric surface. Then, group A was measured under a very low RH level (1%), while group B was stored under high RH (60%) for 60 min, and then was measured under 60% RH. Group C was not dehydrated, and was measured under a low humidity level (1%) similar to group A. The thickness of the adsorbed water layer for group A is therefore smaller than groups B and C. Consequently, the contribution of the meniscus force to the measured adhesive is expected to be much smaller for group A compared to groups B and C. Comparing groups A and B, the influence of the water molecules adsorbed during a time duration of 60 min under high relative humidity (60%) could be assessed. Also, the comparison between groups A and C reveals the influence of the annealing step.

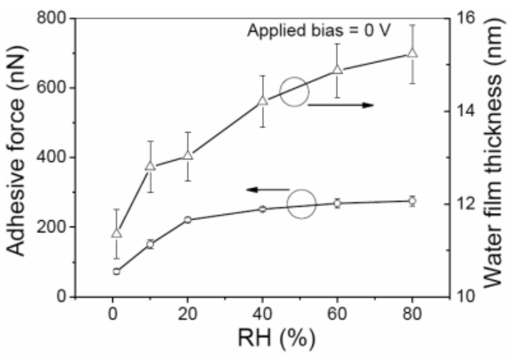


Fig. 2. The influence of the relative humidity on adhesive force and adsorbed water film thickness.

Figure 3 presents the measured adhesive force under different applied bias for the three mentioned sample groups (A, B, and C). For the three groups, the adhesive force is found to increase with the applied bias as shown in Fig. 3a. This increase is attributed to the increase in the attractive electrostatic force between the AFM tip and the SiNx surface as the applied bias increases. In addition, the increase in the adhesive force with bias is found to be very small for group A compared to groups B and C. In these experiments, the adhesive force was measured while the bias is applied between the AFM tip and the sample. So, the SiNx film is charged, and this results in an induced potential over the dielectric surface which reduces the effective applied bias between the AFM tip and the sample. The induced surface potential for the three groups of samples were measured, and the effective applied bias is calculated, and the results are plotted in Fig. 3a.

Figure 3a highlights that for a given applied bias, the effective bias is much smaller for group B compared to group A. Therefore, the electrostatic attractive force for group B is much smaller than group A for all investigated applied bias. In spite of that, the adhesive force measured under different bias for group B is found to be much larger compared to group A. The measured adhesive force as a function of the effective bias is shown in Fig. 3b. It is evident from the figure that at the same effective bias, hence the same electrostatic force, the adhesive force for group B is much larger compared to group A.

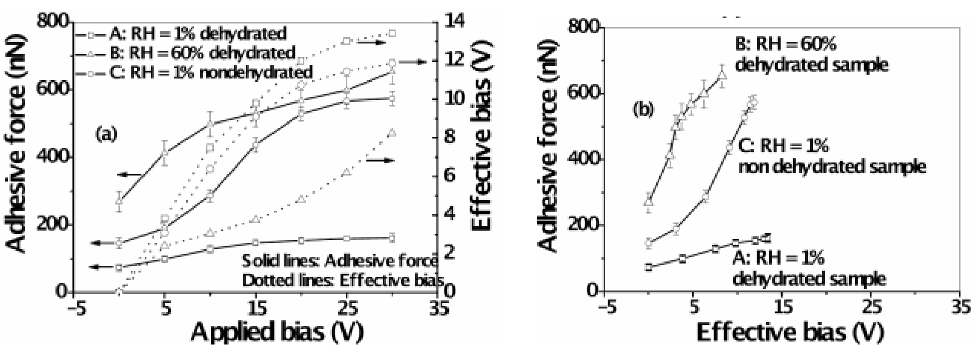
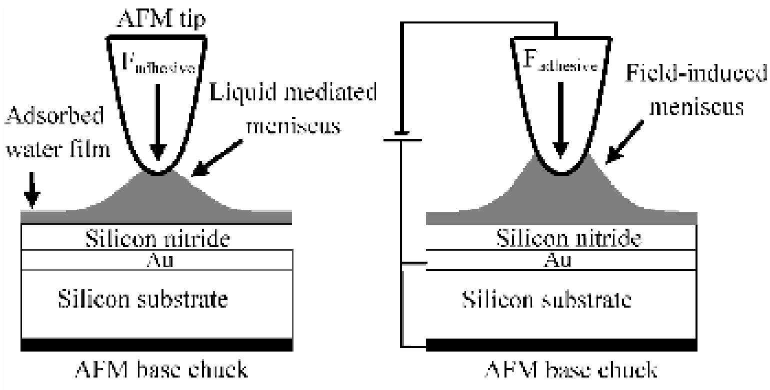


Fig. 3. The impact of applied bias on adhesive force.

Also the increase in the adhesive force with the effective bias is much higher for group B compared to group A. Therefore, the difference in the trend of the adhesive force versus the applied bias between both groups cannot be attributed to the electrostatic attractive force. Additionally, the relatively small difference in the adhesive force between the two groups when no bias is applied clearly indicates that the large difference between both groups at higher bias cannot be explained by the liquid mediated meniscus formation. Since the individual impact of the attractive electrostatic force and the liquid mediated meniscus formation does not explain the high difference in the adhesive force between groups A and B, there must be other adhesion mechanisms.

There are different mechanisms behind the meniscus formation as shown in Fig. 4. When mechanical instability occurs (between points B, C in Fig. 1), the tip jumps into contact with the adsorbed water film and wicks up around it to form a meniscus (Fig. 4a). This is called liquid mediated meniscus. It has been also reported that the adsorbed water film between the AFM tip and the sample surface grows under the influence of the electric field, forming a meniscus that becomes unstable when a critical field is reached [3, 4]. At this point, the meniscus suddenly forms a bridge between the tip and surface as shown in Fig. 4b. This is called a field-induced meniscus. A modeling study shows that the height of the water film under the tip almost doubles upon the formation of the field-induced meniscus [3]. Therefore, the increase in the water film thickness caused by field-induced meniscus is much higher compared to the increase in the water film thickness caused by increasing the relative humidity (see Fig. 2). Also, due to the attraction of water molecules towards the tip under the electric field, the volume of the meniscus surrounding the tip will increase considerably.



a) b)

Fig. 4. Different mechanisms of meniscus formation between the AFM tip and the sample surface.

This leads to the conclusion that the field-induced meniscus and its resulting considerable increase in the water film volume surrounding the tip will result in increasing the adhesive force between the AFM tip and sample surface considerably. Also, the influence of the field-induced meniscus on the adhesive force is expected to be much higher compared to the liquid mediated meniscus formed when no bias is applied.

The threshold voltage required to induce the formation of water bridges between a metallic tip and a flat metallic sample is given by [4]

$$V_{th} = 3.5D\sqrt{\ln(1/RH)} \qquad (1)$$

where D is the distance at which the field-induced meniscus forms, and RH is the employed relative humidity. Based on Eq. 1, for a given tip-sample separation, the required threshold field for the formation of water bridges decreases considerably when the relative humidity increases. For example, at 5 nm tip-sample separation, the calculated value of V_{th} for RH of 1% and 60% are found to be 24.7 V and 8.2 V, respectively.

Figure 3b shows that for sample group B the adhesive force increases considerably at relatively small effective bias (around 5 V), and this increase is attributed to the field-induced meniscus formation. The considerable increase in adhesive force indicates obviously that the threshold field required to induce the formation of liquid bridges between AFM tip and the SiNx surface has been reached. This is supported by the small calculated value of the threshold voltage at 60% RH from Eq. 1 which is 8.2 V. In addition, higher RH would lead to a stronger attractive capillary force since the adhesive force becomes longer ranged as explained earlier. According to that, the field-induced meniscus can persist at a longer tip-sample separation before bridge rupture [7]. Therefore the adhesive force measured at 60% RH (group B) will increase considerably by the field-induced meniscus formation. For group A of samples, the maximum effective bias is found to be larger compared to group B as shown in Fig. 5d. In spite of that the increase in the adhesive force with the effective bias for group A is found to be smaller compared to group B. This indicates that for group A the threshold field required for the field-induced meniscus has not been reached by the range of applied bias used in these experiments. Comparing the adhesive force for groups A and B at higher bias, it can be concluded that at higher RH levels the adhesive force resulting from the field-induced meniscus is much higher compared to the adhesive force caused by the attractive electrostatic force and/or the liquid mediated meniscus.

Two categories of capacitive MEMS switches (switch-A and switch-B) are assumed, which employ the sample groups A and B. When no bias is applied and assuming that the surfaces of both the dielectric film and the switch bridge come in contact with each other, the interface will look like Fig. 5a and Fig. 5b for switch-A and switch-B, respectively. The figures shows that the interfaces of both switches have many contacting and near-contacting asperities. Also the liquid mediated meniscus in switch-B is much higher than switch-A.

When bias is applied in order to actuate the switch, field-induced meniscus will be formed in the positions of contacting and near-contacting asperities for switch-B (Fig. 5d). This might also occur in switch-A if the actuation voltage is large enough to reach the threshold voltage (Fig. 5c). Under any condition, the formation of the field-induced meniscus will be much higher in switch-B compared to switch-A, similar to the obtained results for samples B and A. This results in the formation of a water meniscus between the near-contacting asperities in switch-B as shown in Fig. 5d. Also, the volume of liquid mediated meniscus previously formed at the contacting asperities will increase in switch-B. When the applied bias is removed, the adhesive force between the switch bridge and the dielectric layer occurs under the effect of induced surface potential over the dielectric surface. Since the induced surface potential in sample B is much larger compared to sample A (Fig. 2), the enhancement of the field-induced meniscus in switch-B is much larger compared to switch-A. Also, the attractive electrostatic force in switch-B will be much higher compared to switch-A. Based on this analysis, the adhesive force between the switch bridge and the dielectric film will be much larger in switch-B compared to switch-A.

Based on the previous analysis, the adhesion or stiction between the switch bridge and the dielectric will be much faster in switch-B compared to switch-A. This explains why MEMS switches operated at larger RH have shorter lifetimes as reported in [8]. For switch-B, the main mechanism behind the stiction is the field-induced meniscus formation which is enhanced by the dielectric charging phenomenon. For MEMS switch-A, if the induced surface potential reaches the critical threshold, field-induced meniscus will be formed, and the high resulting adhesive force will cause the switch stiction. If the induced surface potential in the long time range does not reach the threshold voltage, the stiction will be caused by the electrostatic attractive force.

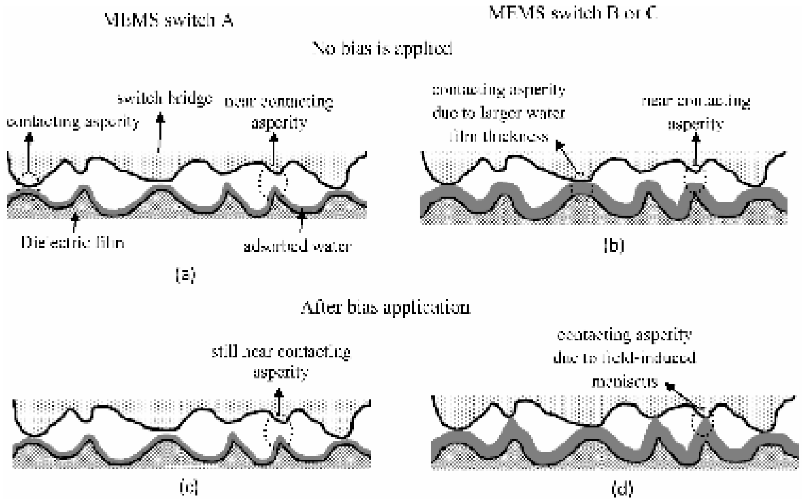


Fig. 5. A cartoon showing the meniscus formation at the interface between the switch bridge and the dielectric film for MEMS switches.

Figure 2 also highlights that the increase in the adhesive force with the applied bias for sample group C is much higher compared to group A. The effective applied bias, hence, the electrostatic force, is relatively smaller for group

C compared to group A. Therefore the higher increase rate of adhesive force with the applied bias for group C compared to group A is attributed to the field-induced meniscus formation. Once again, two types of MEMS switches are assumed, switch-A and switch-C, which resembles the investigated samples A and C, respectively. When bias is applied to actuate switch-C, the volume of the meniscus surrounding the contacting asperities will increase due to the field-induced meniscus formation (Fig. 5d). Also, bridging the near-contacting asperities by water will be further supported by the field-induced meniscus in switch-C. This is because the gap between the near-contacting asperities will be smaller due to the thicker water film in switch-C, and therefore the threshold voltage will be smaller. In other words the field-induced meniscus formation is expected to be much higher in switch-C compared to switch-A. Based on this analysis the stiction between the switch bridge and the dielectric film for switch-C will be much faster compared to switch-A. This explains why annealing MEMS switches increases the device lifetime as reported in [1].

4. Conclusion

The individual impact of the charging induced stiction and meniscus induced stiction in electrostatic capacitive RF-MEMS switches is presented. Also, the interaction between both stiction mechanisms was investigated. The adhesive force resulting from the field-induced meniscus is found to be a dominant stiction mechanism. The adhesive force induced by meniscus formation due to the adsorbed water layer is found to be relatively small when the dielectric layer is not electrically stressed. When bias is applied, the adhesive force increases considerably for dielectric films which have not been annealed even after being measured at a very low humidity level, due to the field-induced meniscus. For the annealed samples, the contribution of the field-induced meniscus is found to be very high when the sample is stored under larger relative humidity for a short time. The nanoscale characterization performed in this study explains well the crucial role of a controlled MEMS packaged environment to control and minimize relative humidity and enhance lifetimes. Also, it explains why annealing MEMS switches increases the device lifetime.

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